A Wireless Medium Access Protocol (CSMA/CD-W) for Mobile Robot based Distributed Robotic Systems

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Abstract

A media access protocol, CSMA/CD-W (Carrier Sense Multiple Access with Collision Detection for Wireless) is proposed to support broadcasting and point-to-point communication in mobile robot based Distributed Robotic Systems (DRS). Distinct from many existing experimental systems built with off-the-shelf wireless communication products for computers, no centralized mechanism such as a communication server, or "ground support" is used, which is consistent with basic principles of DRS. The proposed protocol supports wireless data communication among mobile robots on a shared radio communication channel. It differs from CSMA and its variations with the capability of detecting, in a wireless network, collisions of broadcast (undesignated) messages without using any centralized devices. Satisfactory performance of the protocol is demonstrated with a rigorously designed discrete event simulation.

1. Introduction

1.1 Mobile Robot based DRS

The research on mobile robot based Distributed Robotic Systems (DRS) has received a lot of attention in recent years. It is generally agreed upon that each robot under the DRS model should operate autonomously, while all robots must cooperate to accomplish any system-wide (global) task through limited inter-robot communication [1]. The principles of the DRS model exclude the employment of any centralized mechanism, such as a centralized CPU, a centralized and shared memory, or a synchronized clock. The system consists of only autonomous mobile robots and nothing else. No "ground support" may be employed.

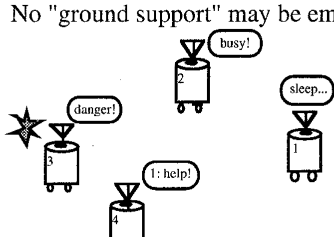

Fig. 1 Interaction among mobile robots in a DRS

By no means that the research on fully distributed robotic systems denounces the importance of centralized and/or hierarchical strategies for multi-agent systems. On the contrary, DRS is complimentary to these strategies for tasks with which distributed parallelism is advantageous; or under situations where a centralized mechanism may break down resulting failure of the entire system. Moreover, many cooperation and coordination tasks carried out by human beings and animal groups are fully distributed in nature, and we certainly want to understand them, and engineering such activities with robots. If we believe that there will be a rapid growth in the robot population, we will be forced to study fully distributed control strategies.

1.2 Inter-Robot Communication

Autonomous mobile robots in a DRS interact through either localized broadcasting (sign-board) [2], or point-to-point communication (message passing) -- not depending on any centralized mechanism such as a centralized communication server, a "blackboard", or other types of ground support.

Many existing experimental DRS test-beds are implemented with off-the-shelf wireless communication systems designed for computers [3]. They employ either a centralized hardware to indicate the network status, or a centralized communication server to relay messages. (For instance, existing wireless Ethernet all have a centralized controller). The presence of a centralized mechanism physically violates the principles of the DRS model.

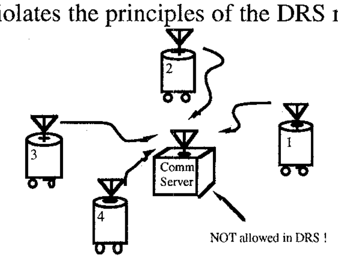

Fig. 2 Centralized comm. server is not allowed in DRS

It should be noted that some experimental DRS systems and simulation platforms employ a centralized communication server with the intention of "simulating" the effect of fully distributed localized broadcasting or point-to-point communication. DRS experiments based on such a system are valid only if the cooperation and coordination algorithms exercised on the platform do not depend, either explicitly or implicitly, on this centralized mechanism. These algorithms will otherwise fail immediately once

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ported to a fully distributed multiple mobile robotic system with the centralized communication server removed.

1.3 CSMA/CD-W

Broadcasting and message passing are two basic mechanisms for autonomous mobile robots to communicate in a DRS. Due to limitations on usable radio bandwidth, a "flat" frequency division multiplexing (FDM), (one robot per communication channel), may not be feasible for a system containing a relatively large number of robots.

Token ring and CSMA (Carrier Sense Multiple Access) are two basic mechanisms of TDM (Time Division Multiplexing). Wireless implementations based on the former are exemplified with Yamabico robot series [4,5]. The DRS research community has expressed great interest of introducing CSMA type protocols into a fully distributed multiple mobile robotic system.

Two problems must be resolved for a CSMA type protocol to operate over a wireless radio communication network under the DRS model. First, since no centralized mechanism or ground support is allowed, existing variations of CSMA/CD (Carrier Sense Multiple Access/Collision Detection) [6] relying on a centralized mechanism to detect and to indicate a collision can not be used. Second, for an autonomous mobile robot to detect collision on the shared radio communication channel, both its transmitter and receiver must be operating at the same time. Since the antennas for the transmitter and that for the receiver can not be placed so far apart on the mobile robot, (in fact, they may have to share the same antenna), the radio energy emitted by the transmitter is so overwhelmingly strong relative to that emitted by other robots at distances that the detection on simultaneous transmissions on a shared radio communication channel is practically impossible.

A medium access protocol, CSMA/CD-W (Carrier Sense Multiple Access with Collision Detection for Wireless), designed for wireless network nodes (in this case, autonomous mobile robots) under DRS is proposed, which avoids these two problems. Similar to CSMA, a robot checks the status of the shared communication channel before attempting a transmission, and waits for a random time after a collision is detected. It differs from CSMA on the method of collision detection -- this is accomplished by monitoring the state of the shared communication channel immediately *after* (instead of *during*) each transmission.

1.4 Paper Organization

Section 2 introduces the CSMA/CD-W protocol. The design principles of the protocol are described in Section 3. In Section 4, a computer discrete event simulation and the experimental results are presented. Section 5 addresses the current and future research directions on this topic.

2. CSMA/CD-W Protocol

2.1 Assumptions and Requirements

A mobile robot constitutes a *node* in the wireless communication network. A single radio communication channel is used as a multi-access medium shared by all nodes. Only one node should transmit at any given time. Simultaneous transmissions from more than one node cause a *collision*.

Unlike a LAN for computer systems, the medium used in this protocol is raw, and is not supported by any centralized hardware for indication of its operating status (IDLE, BUSY OR COLLISION). Consistent to principles of DRS, this control protocol cannot rely on the functionality of any centralized mechanism such as one fixed "master" node.

A radio *transceiver* is equipped on each robot. Tuned into the common communication channel, it is used to transmit/receive data to/from the network. The transceiver normally operates under the receiving mode, except during the transmission of a message.

The protocol operates with arbitrary number of nodes, which may change dynamically.

2.2 Basic Idea

A single radio communication channel (vacuum or air) is used as the raw medium for all nodes. To reduce the probability of simultaneous transmission (collision), a node checks the status of the shared communication channel before a transmission is attempted. If the channel is busy, it waits for a random period of time.

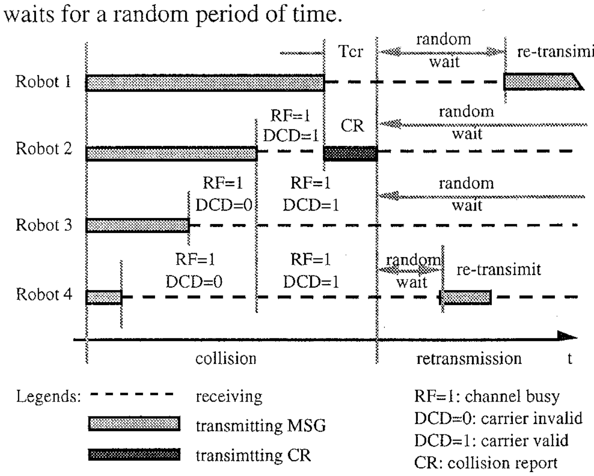


Fig. 3 Collision detection in CSMA/CD-W

There is nevertheless still a small chance for two or more nodes to start transmission at almost the same time, which results a collision. Due to strong radio energy emitted by the transmitter, it is impossible for a node to detect and realize the collision until the transmission is completed.

The protocol is designed such that the length of a message generated by a node is always fixed, and is distinct from that generated by others. Thus if a collision occurs, i.e., more than one node started to transmit at almost the same time, they will end their respective transmissions at different time moments (Fig. 3).

A node checks the status of the channel immediately after each transmission. If the channel is still busy, (RF=1 in Fig. 3), a collision has occurred, as some other nodes are still broadcasting their messages.

Thus all nodes involved are able to realize the collision, except the one which sends the longest message. This node has to be informed by others (about the collision).

A node is instructed to check, in addition to the channel status, the *validity of the carrier*, right after each transmission. The received carrier is valid (DCD=1 in Fig. 3) *iff* modulated signal from the transceiver can be demodulated by the modem -- the received radio signal must have been emitted from a single node.

The difference in message lengths, the data transmission rate and the speed of protocol execution are specified in such a way (see Section 3) that a node detects a valid carrier if and only if it has involved in a collision with the second longest message. This node is responsible for generating a collision report [CR] message to inform the node which sends the longest message.

For a node involved in the collision with the third longest or a shorter message, its received carrier at the time of checking is invalid (DCD=0 in Fig. 3). Because at the moment when it completed its transmission, more than one nodes (at least, nodes with the longest and the second longest message) are still transmitting. The protocol instructs a node to wait for a predetermined period of time (T_{cr}) for the possible [CR], even if the channel is not busy after the transmission. If a [CR] is received during the waiting period, a collision must have occurred. Otherwise, the transmission is successful.

Thus if a collision occurs, all nodes involved are able to realize the collision. A re-transmission is attempted after a random waiting period.

2.3 Hardware

Hardware of the system (on each robot) consists of a transceiver, a modem, a HDLC controller and a micro-controller (μC), which not only boperates the communication protocol, but also serves as the interface between the robot and its communication subsystem (Fig. 4). The following signals must be presented to the protocol control running on the micro-controller.

- [RF] (Radio Frequency detected): a boolean signal. RF=1 *iff* channel is busy (someone is transmitting.
- [DCD] (Data Carrier Detected): a Boolean signal. DCD=1 *iff* the carrier entering the modem is valid indicating a single node is transmitting.

The RF signal for monitoring radio transmission is easily derived from the transceiver. The DCD for monitoring carrier is the *Data Carrier Detect* output from the modem. HDLC frames are captured, and assembled by a HDLC controller. In fact all of above except the μC, is available as a chip by PROXIM [7] (Fig. 4).

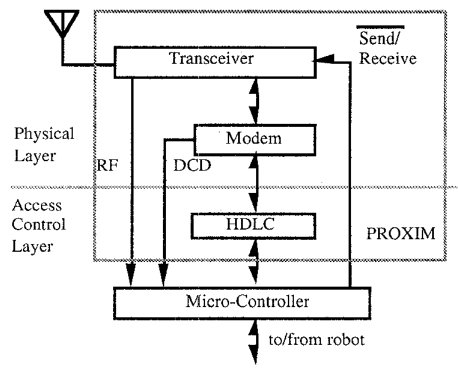


Fig. 4 Hardware supporting CSMA/CD-W

2.4 Protocol Control

Receiving

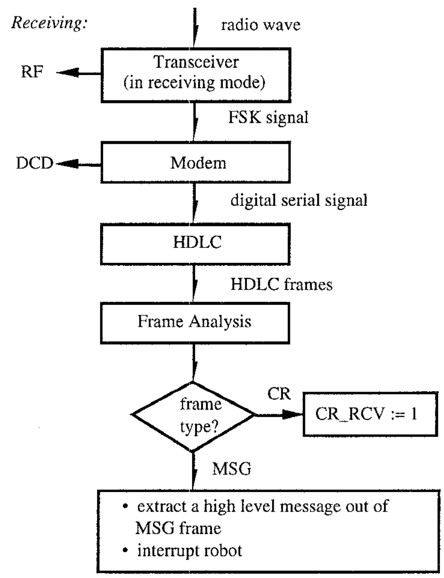


Fig. 5 Receiving process

The *receiving process* (Fig. 5) classifies all incoming messages into two categories, MSG or CR. If a message of type CR is received, a variable *CR_RCV*, shared with the *transmitting service*, is set. Otherwise, an interrupt to robot processes is generated. As the receiving process operates continuously, except during transmission, no messages originated from other robots are to be omitted.

Transmitting

Implemented according to the collision detection scheme described in Section 2, the *transmitting service* is called upon whenever a robot intends to send a message.

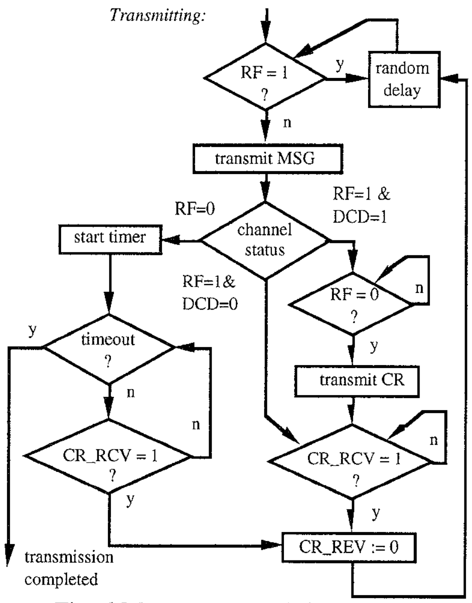


Fig. 6 Message transmitting service

3. Protocol Design

3.1 Resolution R

The protocol requires that the length of a message originated by a node be fixed, and distinct from that of others. Without losing generality, we assume that robots are labeled with identifications -- 0, 1, 2, ..., and the length of messages for robot i is $L+i\cdot R$, where L is the basic length of messages, and R is called the *resolution*. Both L and R are constants. Thus the length difference between messages originated by robot i and that by robot $i+1$ is R.

Let T_x be the time needed for a node to switch from receiving mode to transmitting mode or vice versa. T_x *is* called *mode switching time*. In the worst case (Fig. 7), robots $i+1$ determines to start a transmission at time t_0, and the channel will not become BUSY until time t_0+T_x, (transmission will not start until robot $i+1$ switched from receiving mode to transmitting mode. At time t_0+T_x, robot i may decide to transmit (as the channel was not BUSY). A collision occurs. Messages generated by robot $i+1$ must last long enough to be detected by robot i after its transmission (of a message one R shorter), and a mode switching (from transmitting to receiving).

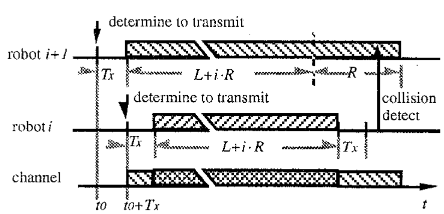


Fig. 7 Determining the resolution R

From Fig. 7, we see that if ρ is the baud rate for data transmission, we must have $(L+(i+1)\cdot R)/\rho > 2\cdot T_x + (L + i\cdot R)/\rho$, or $R > 2\rho\cdot T_x$. It is clear that the longer T_x is, the higher the possibility of collision will be. As collision is the main cause of deteriorating the performance of this protocol, T_x must be reduced to a minimum.

3.2 Channel Status Checking

Let robot i be the one sending the longest message, and robot j be that the second longest, and they complete their transmissions at time t_i and t_j, respectively. A collision occurs as shown in Fig. 8.

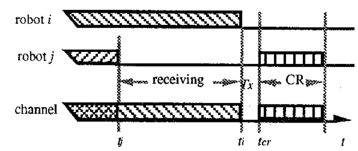


Fig. 8 Channel is not BUSY before a CR

According to the protocol, it is the responsibility of robot j to send a CR. But robot j needs T_x time to switch from receiving mode to transmitting mode, during which time (between t_j and t_{cr}) the channel is actually not BUSY. This would allow another robot not involved in the collision to start transmission, if the status checking on the channel were a simple, instantaneous operation. Therefore, status checking on the channel must be implemented as a time delay for at least T_x, followed by a snapshot.

3.3 Other Comments

- As a collisions is detected after (not during) a transmission, this protocol is expected to be less efficient than other CSMA/CD protocols supported by centralized hardware. However, if T_x is sufficiently small, so will be the rate of collision. The system performance approaches that of ordinate Ethernet as $T_x \to 0$. This has been verified by the discrete event simulation presented in the next section.
- Many high level operating primitives for DRS such as distributed mutual exclusion can be effectively and efficiently implemented taking advantage of this protocol [8]. Since the communication channel is shared by all robots, at most one message is transmitted at any given time -- all messages successfully transmitted over the communication channel are effectively *serialized*. The problem of competing for the right of accessing a resource pool is therefore reduced to that of competing for transmitting a special type of message to the shared channel.
- The protocol is readily implementable with commercially available hardware (PROXIM chip and a micro controller). Dramatically reduction of the mode switching time (T_x) is expected.

4. Performance Evaluation

4.1 Simulation Design

Considerations were made to ensure the discrete event simulation to truly represent the model, and to reflect the asynchronous and distributed nature of the protocol.

- Time was assumed to be continuous with a resolution of 1 ns or less, which is $1/10^6$ of the mode switching time specified by the PROXIM chip; and three (3) orders of magnitude lower than the time needed to transmit a bit to the shared wireless channel.
- Mode switching time (T_x), and the time needed for software execution (of the protocol) was considered.

Discrete events encountered while operating the protocol are summarized as follows:

- request for transmission from a robot
- end of checking channel status
- start to switch into transmission mode
- start to transmit a message
- start to transmit a CR
- end of transmission
- start to switch from transmission to receiving
- start waiting until timeout or collision report
- wait until collision report is heard
- wait until the channel is free
- wait until a new transmission attempt

Poisson distributions with various constant means were used in determining the random interval between message transmitting requests and the random waiting time (with mean α in ms).

4.2 Parameter Selection

Simulation parameters were selected according to a realistic (commercial available) wireless communication device (PROXIM 200). They include

- transmission rate: 100-200 kbs
- mode switching time (T_x): 1 ms
- number of robots: 5
- time to transmit a message: 10 ms (1 kb at 100 kbs)
- time to transmit a CR: 2 ms
- timeout for CR: 5 ms
- simulation time: 100-1000s

The simulation time was chosen to ensure the system reaches an equilibrium state, and longer simulations would not improve the margin of error, or vary the results. Other parameters introduced to represent various operating conditions include:

- request rate: with a mean in the range of 1 to 50 messages per second
- random waiting time (α): with a mean in the range of 5 to 100 ms

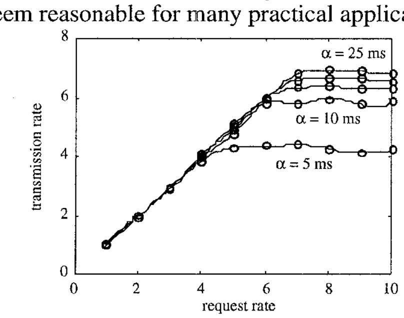
4.3 Statistics Collected

The following key statistics are collected under various experimental conditions:

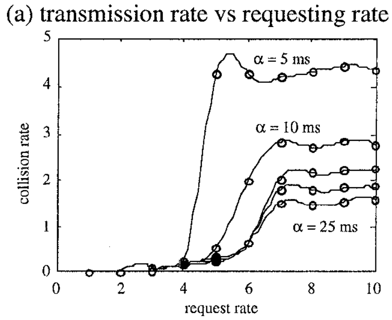
- transmission rate: number of messages transmitted per second over the shared communication channel
- collision rate: number of collisions per second
- percent idle time: percentage of time during which the channel is idle

4.4 Results with Specifications of PROXIM Chip

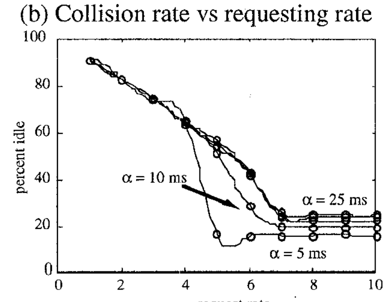
It is observed (Fig. 9) that, with the PROXIM chip,, the system may achieve a transmission rate of about 8 messages/second for a group of 5 robots. The channel utilization under these conditions is about 70% -- about 15% of which is used for transmitting collision reports. The results seem reasonable for many practical applications.



(a) transmission rate vs requesting rate



(b) Collision rate vs requesting rate

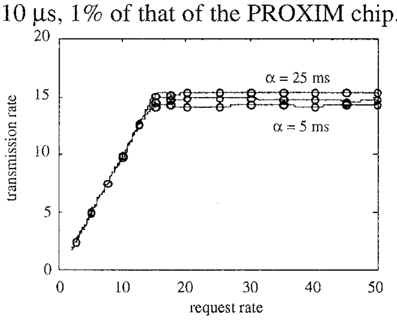


(c) Channel idle time vs requesting rate

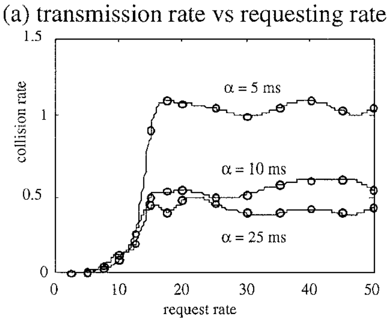
Fig. 9 System performance using specs of PROXIM

4.5 Results with Reduced Mode Switching Time

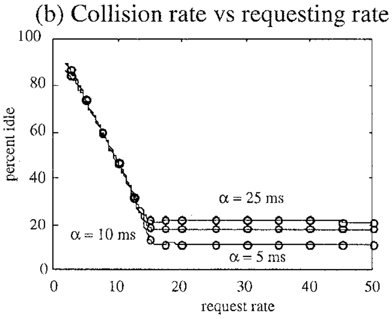
The effect of reduced mode switching time (T_x) was also investigated. Fig. 10 is the simulation result when T_x is reduced to 100 μs, about 1/10 of its original value. The transmission rate is doubled at 16 messages/second -- very close to the maximum rate possible for the involved number of robots (5). Collision rate is significantly decreased. Our simulation reports virtually no collision with about 90% channel utilization when the switching time is further reduced to 10 μs, 1% of that of the PROXIM chip.



(a) transmission rate vs requesting rate



(b) Collision rate vs requesting rate



(c) Percentage of idle time vs requesting rate

Fig. 10 System performance with $Tx = 100\ \mu s$

5. Current and Future Research

Current and future research topics for CSMA/CD-W:

- Formal specification and verification on the correctness of CSMA/CD-W.
- Design and implementation of inter-robot communication subsystem for autonomous mobile robots supporting CSMA/CD-W.
- Derivation of resource sharing strategies taking advantage of the CSMA/CD type protocol.
- Adaptation of the resource sharing strategies based on CSMA/CD-W to a fully distributed traffic control system with autonomous mobile robots operating on discrete space [9].

6. Conclusion

The DRS research community has expressed great interest of porting CSMA/CD type protocols to a wireless communication network composed of multiple autonomous mobile robots. Using no centralized mechanism (hardware or communication server), CSMA/CD-W is able to detect and resolve collisions on a shared communication channel.

Design principles for the protocol are discussed. A series of computer discrete event simulations show that CSMA/CD-W is promising for mobile robot based DRS using commercially available hardware (PROXIM chip). Improvement on mode switching time enhances the protocol to approach the performance of ordinary CSMA/CD supported by centralized hardware.

7. References

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